Received: 7 October 2019 | Revised: 17 October 2019 | Accepted: 18 October 2019
DOI: 10.1002/mdp2.111

SPECIAL ISSUE ARTICLE

WILEY

Effect of wall thinning on deformation and failure of copper-nickel alloy elbows subjected to low cycle fatigue

Muhammad Faiz Harun[1] | **Roslina Mohammad**[1] | **Andrei Kotousov**[2]

[1] UTM Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia
[2] School of Mechanical Engineering, The University of Adelaide, Adelaide, South Australia, Australia

Correspondence
Dr Roslina Mohammad, Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia, Razak Tower, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia.
Email: mroslina.kl@utm.my; puteriadelaide@yahoo.com

Funding information
Razak Faculty of Technology and Informatics and Universiti Teknologi Malaysia (UTM), Grant/Award Number: R. K130000.7840.4F852 Q. K130000.2540.19H15 Q. K130000.2656.16J42 Q. K130000.2540.19H15; Ministry of Higher Education, Malaysia, Grant/Award Number: MyBrain15 MyPhD

Abstract
Various industrial standards and safety regulations specify the minim number of cycles, which pressure equipment must tolerate during a single seismic event. The compliance with these standards and regulations is necessary in order to ensure safety and strength of critical structural components, eg, pressure pipe system of the primary coolant loop of nuclear reactors or condensed water supply of large hospitals or other large facilities. However, the strength can degrade with time due to flow accelerated corrosion causing wall thinning. Pipe bends are particularly susceptible to the localised corrosion, and, therefore, these structural elements need a special consideration. The current paper studies the effect of localised corrosion on low cycle fatigue behaviour of a copper-nickel elbows using experiment and finite element method (FEM). The outcomes of the study demonstrate a quite low reduction of low cycle fatigue life even at severe local wall thinning at different locations.

1 | INTRODUCTION

Pipe bends and elbows are common structural elements and often represent the weakest link[1] in pressure piping during extreme loading such as earthquakes.[2,3] Therefore, their performance and behaviour during seismic events are critical from the structural integrity point of view. Various industrial standards, such as ASME and the Japanese JEAC, specify the minimum number of cycles, which pressure equipment must tolerate during a single seismic event.[4-7] However, bends and elbows over time are subjected to the flow accelerated corrosion leading to the localised wall thinning.[8-10] Therefore, it is important to understand the effect of these structural defects on the strength in order to maintain the safety and integrity of hazardous structures. This problem was also emphasised during investigations of the integrity and residual strength of piping containing wall thinning defects after recent powerful earthquakes in Japan.[11]

In the case of extreme event (eg, earthquake or shut down), the piping elements are subjected to high amplitude loading excursions, leading to material cycling in low cycle fatigue regime.[12,13] There were many analytical, numerical, and experimental studies in this area with the ultimate aim of developing a method for the evaluation of low fatigue strength of various piping elements with various wall thinning defects with and without internal pressure.[2,10,11,14-25] For steel elbows, the recent studies have demonstrated that when the elbows are subjected to high amplitude cyclic loading, the cross-section geometry distorts and bulges progressively with number of cycles, while the failure mechanism is largely associated with the initiation and propagation fatigue cracks.[11,18]

The focus of the current study is the effect of the localised wall thinning on the low cycle fatigue resistance of elbows made of copper-nickel alloy. For this purpose, a series of full-scale tests has been conducted under displacement-controlled loading conditions. The experimental study has motivated the development of the 3D elastoplastic finite element model (FEM) to assist with the interpretation of the outcomes of experimental studies.

2 | DETAILS OF EXPERIMENTAL AND NUMERICAL STUDY

Pipe elbows (or 90° bends) were made of C70600 copper-nickel 90/10 alloy (90% copper and 10% nickel), which is a common material for piping equipment. The test specimens consisted of the pipe elbow and two straight pipe segments that joined together by welding. The welding was completed using tungsten inner gas (TIG) welding machine. The outer diameter and wall thickness were 108 and 2.5 mm, respectively. The ratio of straight pipe segment length to the pipe outer diameter was about 3.2, which was consistent with the previous studies.[15] Other main dimensions are provided in Figure 3.

The specimens were tested with configuration as shown in Figure 1A, at the room temperature utilising a universal testing machine INSTRON 5982. One end (the lower end) of the specimens was attached to the testing machine grip through a pin joint, and another end (the upper end) was subjected to cyclic displacement-controlled loading with the displacement range of ±20 mm. The specimens were equipped with strain gauges as illustrated in Figure 1B, which were attached to intrados, extrados, and the crown areas of the elbow. The collected strain data were used to validate the numerical model.

Flow-induced corrosion defects (wall thinning) of various severity were introduced by machining the inner pipe surfaces near the crown, intrados, and extrados areas, as illustrated in Figure 2. The severity of the local thinning is characterised by the different ratio of the machining depth to the wall thickness (t/h). The specimens with the following range of values were tested: 0.25, 0.5, and 0.75.

In this investigation, a total of nine specimens were prepared with wall thinning was created on the elbow using machining process. The machining process was done using CNC milling. Each specimen only has one wall thinning spot with specific depth ratio either at intrados, crown, or extrados. The test was done until failure happen. The failure was indicated by observing the appearing of crack using naked eyes.

In order to support experimental studies a 3D elastoplastic FEM was developed in order to investigate the stress and strain field in other than the strain gauge locations. The geometry of the model and the mesh, which was based on the hexahedral finite elements (FEs), are shown in Figure 3. A denser mesh was used in the middle of the specimen where the large gradients of stress and strain were expected. The mesh convergence tests were done, and the optimum configuration achieved with the total number of elements and number of nodes is 54 227 and 96 222, respectively.

The finite element analysis (FEA) in this study was performed using Ansys Workbench 18.1 using an APDL solver and model was prepared using Ansys SpaceClaim 18.1. The strain-life approach was used to estimate the low cyclic fatigue of the model. The material behaviour of this FEA was based on elastoplastic hardening solid with rate-independent category.[26]

In this study, the kinematic isotropic hardening model was used in order to simulate the material behaviour under cyclic loading. The constitutive equation was based on the linear elasticity, von Mises yield function, and associative plastic flow rule.

The material constants utilised in the numerical study are presented in Table 1.

where E is Young modulus and K' and n' are the cyclic hardening coefficient and exponent of the stabilised cyclic of the stress in the Ramberg-Osgood equation, which was utilised to model the inelastic response of the material and strain curve; ε is total strain range, ε_e is the elastic strain range, and ε_p is the plastic strain range. The data above obtained from curve fitting method on the experimental strain-life curves and cyclic stress-strain curve.

The failure is evaluated using the standard the Basquin-Coffin-Manson criterion,[27] which can be written as

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f'}{E}(2N)^b + \varepsilon_f'(2N)^c. \qquad 2$$

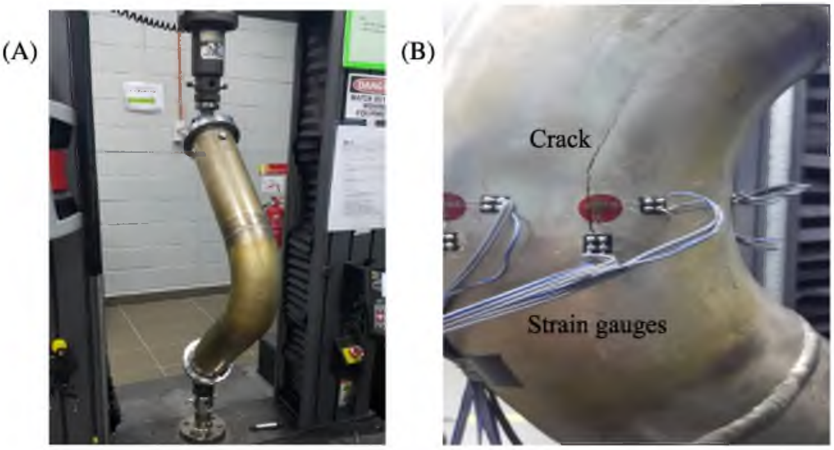

FIGURE 1 A, Elbow test specimen. B, Locations of strain gauges and failure (crack)

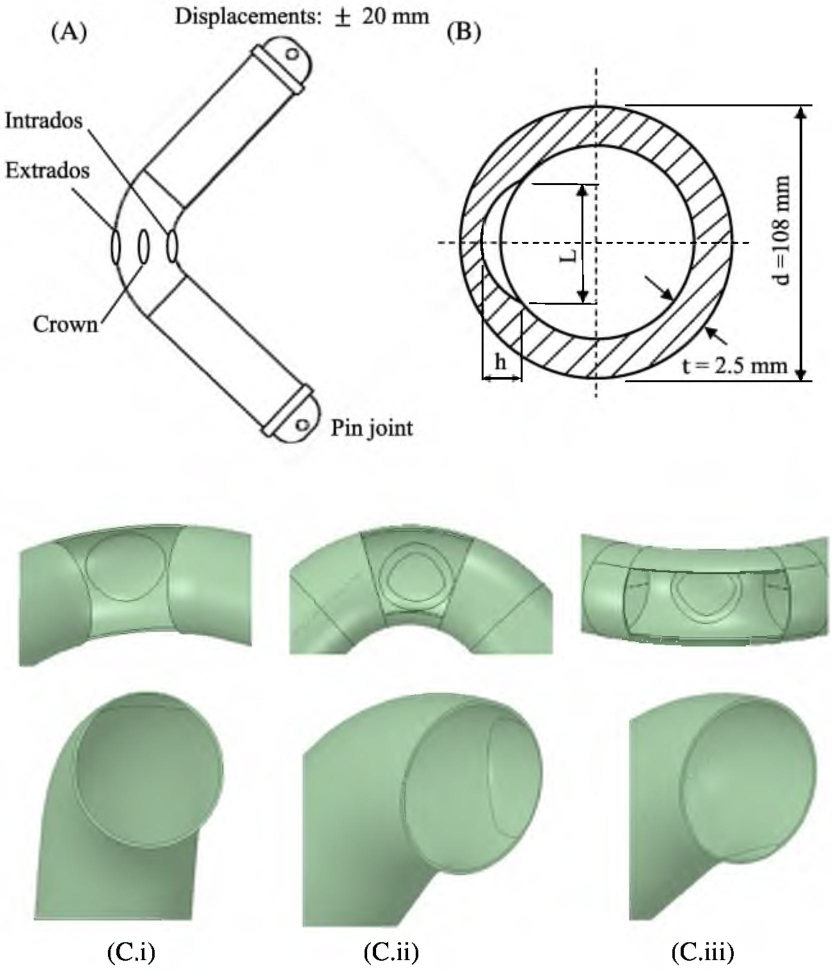

FIGURE 2 A, Test specimen and the areas of wall thinning; B, Cross sectional area and detect dimensions; and 3D elbow model with thin wall at (C.i) extrados, (C.ii) crown, and (C.iii) intrados

3 | OUTCOMES OF NUMERICAL AND EXPERIMENTAL STUDIES

The typical FE strain results are shown in Figure 4 indicating that the critical location is in the crown area on the inner wall, which agrees with the experimental findings, see Figure 1B and Table 2.

Figures 5 and 6 show the typical results of both FE (dotted lines) and experiment studies (solid lines) for the reaction force (Figure 5) and longitudinal strains at the crown location (Figure 6). A good agreement can be observed from these

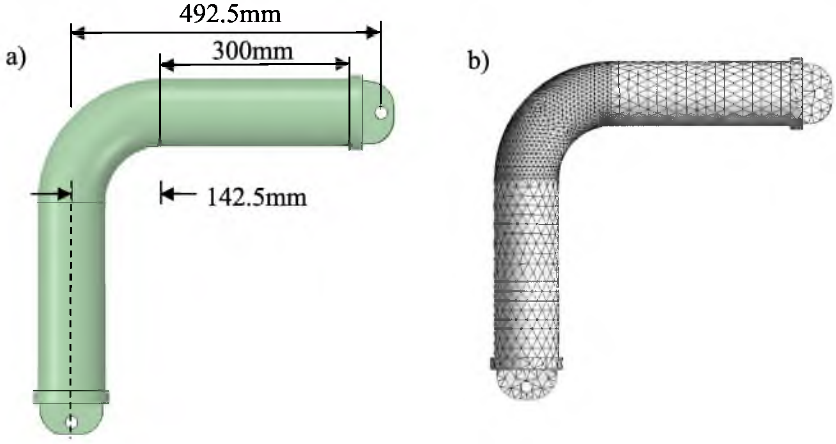

FIGURE 3 A, Main dimensions of the test specimen. B, Finite element (FE) mesh

TABLE 1 The values of the material constants

E, GPa	*K′*	*n′*	σ_f'	ε_f'	*b*	*c*
121.94	523	0.2172	6.9E+08	0.6	−0.13	−0.7

$$\frac{\Delta\varepsilon}{2}=\frac{\Delta\varepsilon_e}{2}+\frac{\Delta\varepsilon_p}{2}=\frac{\Delta\sigma}{2E}+\left(\frac{\Delta\sigma}{2K'}\right)^{1/n'} \quad (1)$$

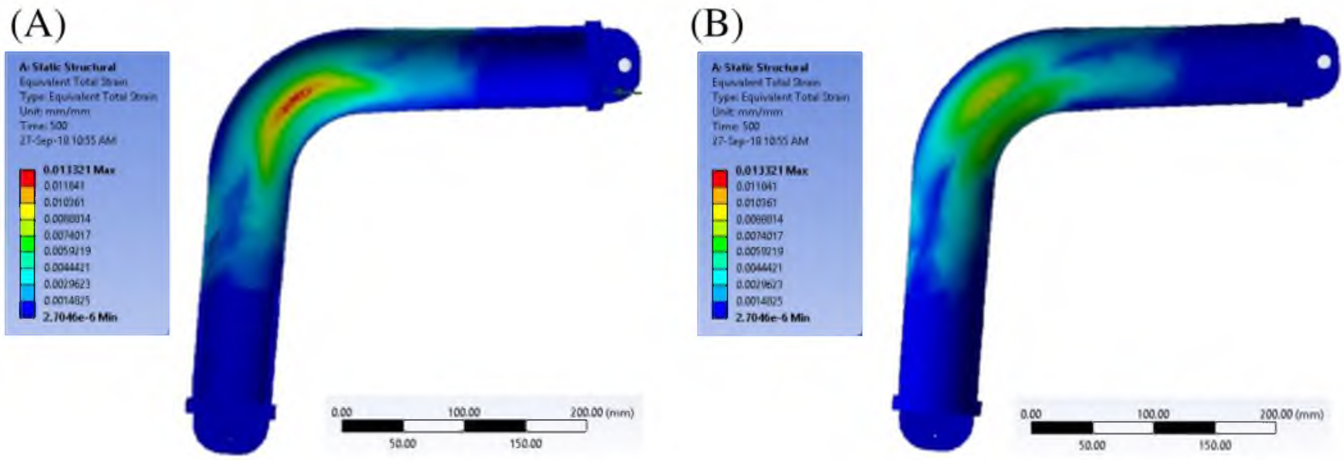

FIGURE 4 Equivalent plastic strains after 208 cycles. A, Inner wall view; B, outer wall

TABLE 2 Summary of experimental and FEM results

	Eroded Ratio (*h*/*t*)								
	Extrados			**Crown**			**Intrados**		
Life (N_f)	**0.25**	**0.5**	**0.75**	**0.25**	**0.5**	**0.75**	**0.25**	**0.5**	**0.75**
Experiment	193	187	179	184	172	166	201	198	194
FEM	195	190	175	181	169	161	203	196	189

Abbreviation: FEM, finite element method.

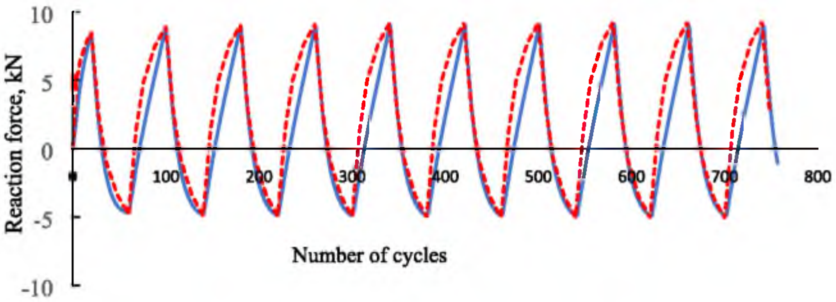

FIGURE 5 Reaction force during elbow cycling: Finite element (FE) results (dotted line) and experimental measurements (solid line)

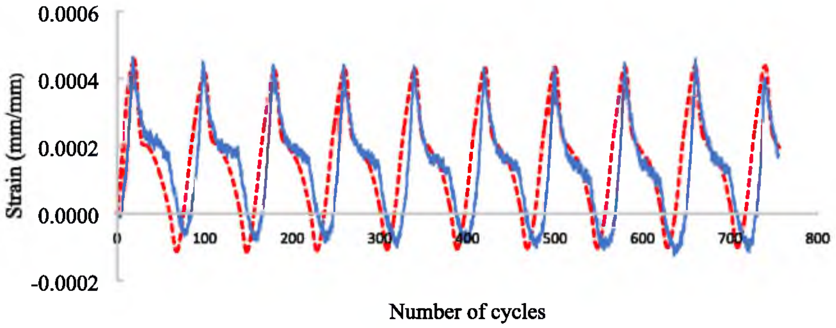

FIGURE 6 Comparison of finite element analysis (FEA) and experimental data strain gauge measurements

figures indicating that a careful FE analysis is capable to describe low cycle fatigue response. The change in slope of strain evolution shows the complexity strain at that location.

Table 2 presents the experimental and FEM data summarising the number of cycle to failure (crack initiation), N_f, for elbows with different wall thinning location: extrados, crown, and intrados, see Figure 2. The uses of the appropriate numerical model together with correct input data have effectively produced a reliable outcome which is nearly equal with actual results. The combination of isotropic and kinematic hardening rule model has tremendously come out with great results especially in terms of simulating the material plastic behaviours under cyclic loading.

The experimental results indicate that the location of the wall thinning (extrados, crown, and intrados; see Figure 2) does not significantly affect the low cycle fatigue life of copper-nickel alloy elbows. In the case of this investigation, it seems that the wall thinning at the crown location has the largest impact on low cycle fatigue strength. However, this impact is quite small, even for sever thinning $h/t = 0.75$) the reduction in the fatigue strength is only 10%, which is comparable with the scatter in experimental results.

4 | CONCLUSIONS

In this paper, the effect of localised corrosion (or wall thinning) on low cycle fatigue behaviour of a copper-nickel alloy elbows was investigated experimentally and using FEA. It was demonstrated that the actual deformations at the critical locations can be accurately predicted by FEM. Therefore, the further investigations can rely on the FE modelling with a limited number of full-scale tests.

The outcomes of the experimental studies demonstrated a quite low reduction of low cycle fatigue life of the elbows even at severe local wall thinning. The latter conclusion agrees well with the previous experimental studies for steel components.

ACKNOWLEDGEMENTS

The authors would like to express their greatest appreciation and utmost gratitude to the Ministry of Higher Education, Malaysia, for awarding the Fundamental Research Grant Scheme, MyBrain15 MyPhD, and Razak Faculty of Technology and Informatics and Universiti Teknologi Malaysia (UTM) for all the support towards making this study a success. FRGS UTM Vote No: R.K130000.7840.4F852, UTM Vote No: Q.K130000.2540.19H15, and UTM Vote No: Q.K130000.2656.16J42.

CONFLICT OF INTEREST

The authors confirm that there are no known conflicts of interest associated with this publication

AUTHOR CONTRIBUTIONS

M.F. Harun, R. Mohammad, and Andrei Kotousov contributed to the design and implementation of the research, to the analysis of the results, and to the writing of the manuscript.

ORCID

Roslina Mohammad https://orcid.org/0000-0003-3789-3706

REFERENCES

1. Chen, X. H., & Chen, X. (2013, November). Numerical simulations of pressurized elbow under reversed in-plane bending. In *Advanced Materials Research* (Vol. 785, pp. 16-19).
2. Li, X. H. (2012, January). Hoop membrane stress analysis of elbow-pipe under single internal pressure. In *Applied Mechanics and Materials* (Vol. 130, pp. 1785-1788).
3. Lu, X. Y., Li, X. G., Liu, J. M., Lu, X. L., Zhu, H. L., & Zhou, Y. (2015, January). Numerical simulation of flow fluid in elbow pipe based on FLUENT and the establishment of the pressure model. In *Applied Mechanics and Materials* (Vol. 713, pp. 39-42). Trans Tech Publications.
4. Hasegawa K, Miyazaki K, Nakamura I. Failure mode and failure strengths for wall thinning straight pipes and elbows subjected to seismic loading. *Journal of Pressure Vessel Technology*. 2008;130(1):011404-1-011404-8.
5. Nakamura I, Otani A, Shiratori M. Failure behavior of piping systems with wall thinning under seismic loading. *Journal of Pressure Vessel Technology*. 2004;126(1):85-90.
6. Ravikiran A, Dubey PN, Agrawal MK, Reddy GR, Singh RK, Vaze KK. Experimental and numerical studies of ratcheting in a pressurized piping system under seismic load. *Journal of Pressure Vessel Technology*. 2015;137(3):1-7.
7. Van KD, Moumni Z. Evaluation of fatigue-ratcheting damage of a pressurised elbow undergoing damage seismic inputs. *Nuclear Engineering and Design*. 2000;196(1):41-50.
8. Gao, B. J., Chen, X., Zhang, S. F., & Li, J. H. (2007, December). A proposed thickness distribution of elbow resisting ratcheting. In *Key Engineering Materials* (Vol. 353, pp. 377-380).
9. Firoozabad ES, Jeon BG, Choi HS, Kim NS. Failure criterion for steel pipe elbows under cyclic loading. *Engineering Failure Analysis*. 2016;66:515-525.
10. Kim JW, Na YS, Lee SH. Experimental evaluation of the bending load effect on the failure pressure of wall-thinned elbows. *Journal of Pressure Vessel Technology*. 2009;131(3):1-8.
11. Urabe Y, Takahashi K, Sato K, Ando K. Low cycle fatigue behavior and seismic assessment for pipe bend having local wall thinning-influence of internal pressure. *Journal of Pressure Vessel Technology*. 2013;135(4):1-5.
12. Takahashi K, Ando K, Matsuo K, Urabe Y. Estimation of low-cycle fatigue life of elbow pipes considering the multi-axial stress effect. *Journal of Pressure Vessel Technology*. 2014;136(4):1-8.
13. Takahashi K, Tsunoi S, Hara T, et al. Experimental study of low-cycle fatigue of pipe elbows with local wall thinning and life estimation using finite element analysis. *International Journal of Pressure Vessels and Piping*. 2010;87(5):211-219.
14. Takahashi K, Watanabe S, Ando K, et al. Low cycle fatigue behaviors of elbow pipe with local wall thinning. *Nuclear Engineering and Design*. 2009;239(12):2719-2727.
15. Urabe Y, Takahashi K, Abe H. Low cycle fatigue evaluation of pipe bends with local wall thinning considering multi-axial stress state. *Journal of Pressure Vessel Technology*. 2015;137(4):1-9.
16. Urabe Y, Takahashi K, Ando K. Low cycle fatigue behavior and seismic assessment for elbow pipe having local wall thinning. *Journal of Pressure Vessel Technology*. 2012;134(4):1-5.
17. Urabe Y, Takahashi K, Matsuo K, Sato K, Abe H. Theoretical study on low cycle fatigue strength of elbows with local wall thinning. *Nihon Kikai Gakkai Ronbunshu, A Hen/Transactions of the Japan Society of Mechanical Engineers, Part A*. 2013;79(804):1303-1316.
18. Varelis GE, Karamanos SA. Low-cycle fatigue of pressurized steel elbows under in-plane bending. *Journal of Pressure Vessel Technology*. 2015;137(1):1-10.
19. Michael TC, Veerappan AR, Shanmugam S. Effect of internal pressure and shape imperfections on plastic loads of pipe bends under in-plane closing moment. *Engineering Fracture Mechanics*. 2013;105:1-15.
20. Duan, Z. X., & Shi, K. (2013, November). Analysis and experiments on the plastic limit load of elbows under combined pressure and in-plane closing bending moment. In *Advanced Materials Research* (Vol. 774, pp. 1090-1097).

21. Simha CHM. Limit load solutions for cracked elbows subjected to internal pressure and in-plane bending. *Journal of Pressure Vessel Technology*. 2012;134(4):1-11.
22. Zhang, S. H., Zhao, D. W., & Gao, C. R. (2012, January). Limit analysis of defect-free pipe elbow under internal pressure with MY criterion. In *Applied Mechanics and Materials* (Vol. 127, pp. 79-84).
23. Chattopadhyay J, Kushwaha HS, Roos E. Improved integrity assessment equations of pipe bends. *International Journal of Pressure Vessels and Piping*. 2009;86(7):454-473.
24. Lee SM, Choi YH, Chung HD, Chang YS, Kim YJ. Plastic limit analysis of an elbow with various wall-thinning geometries. *In Key Engineering Materials*. 2008, December;385:833-836.
25. Vishnuvardhan S, Raghava G, Gandhi P, Goyal S, Gupta SK, Bhasin V. Ratcheting strain assessment in pressurised stainless steel elbows subjected to in-plane bending. *Procedia Engineering*. 2013 Jan 1;55:666-670.
26. Mechanical APDL and Mechanical Applications Theory Reference: Release 15.0 (2013). USA, SAS IP, Inc: ANSYS
27. Basquin OH. The exponential law of endurance tests. *In Proc Am Soc Test Mater*. 1910;10:625-630.

How to cite this article: Harun MF, Mohammad R, Kotousov A. Effect of wall thinning on deformation and failure of copper-nickel alloy elbows subjected to low cycle fatigue. *Mat Design Process Comm*. 2020;2:e111. https://doi.org/10.1002/mdp2.111